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Review of Turkey's current energy status: A case study for wind energy potential of Çanakkale province

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ABSTRACT

Turkey is a free market economy that is oriented towards Western markets. It also has strong ambitions to join the European Union and this factor has been beneficial but also taxing with respect to its changing economic situation. Turkey imports nearly 70% of its energy requirements. The country spends 40–50% of its total export income to import fuel, mainly crude oil and natural gas. On the other hand, Turkey has significant wind energy potential because of its geographical characteristics, such as its shoreline and mountain-valley structures. The sea fronts of the Agean, Marmara, Mediterranean, and Black Seas, and some places of the Southeast Anatolian belt have a high wind potential, with an average speed of 4.5–10 m/s. Studies put wind-energy potential in terms of the technical aspects in the region of 80 GW.

Çanakkale province that has more than 10% of the country's total installed wind power has been presently chosen for the case study. In the present study, hourly time-series wind data recorded from the year 2000 to 2005 at a height of 10 m in Çanakkale city centre and Bozcaada, an island in the Aegean Sea belonging to the Çanakkale province, has been statistically analysed. Overall, Bozcaada, with an annual mean density value higher than 350 W/m^2, offers a much higher wind potential than the former location, indicating sufficient wind potential for large scale electricity generation. The mean power density value in the northeastern direction is highest for the typical year in Bozcaada with a value of 901.6 W/m^2, while the directional power density distribution shows that over 60% of the wind energy comes from the band between northern and northeastern directions.

Contents

1. Introduction

Turkey is made up of a European part, Eastern Thrace, and an Asiatic part, the Peninsula of Anatolia, separated by the Dardanelles, the Sea of Marmara and the Bosphorous. Eastern Thrace located in the southeast of the Balkan Peninsula, makes up less than one-thirtieth of the country's total land area. Anatolia is a mountainous area with many lakes and wetlands. The Ponticas range in the north and the Taurus range in the south form the natural boundaries for the Anatolian Plateau, which extends eastward to form the Armenian plateaus [1]. Turkey is one of the largest economies within the Balkan region achieving an average annual growth rate of 5.6% over the past 25 years and a GDP/capita of 9980 Euro (in 2009). Strong population growth of 1.45% per annum and rapid urbanization has played an important role for development of Turkey.

Turkey is a free market economy that is oriented towards Western markets. It also has strong ambitions to join the European Union and this factor has been beneficial but also taxing with respect to

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Table 1
Energy statistics for Turkey.

	2005	2006	2007	2008
Gross inland consumption of primary energy, 1000 toe	85,355	94,664	101,510	100,318
Final energy consumption, 1000 toe	13,398	14,883	16,947	16,254
Energy dependency on imports, %	71.9	72.5	74.4	–

Table 2
Turkey's population, economy and energy use.

Year	Population, million	GDP/capita, $	Energy use, kgoe/capita
1990	56.5	4628	942
2000	67.8	9134	1140
2007	70.6	12,890	1370
2008	71.5	13,138	–
2009	72.5	12,339	–

Note: 1 kgoe = 11.63 kWh.

its changing economic situation. Turkey imports nearly 70% of its energy requirements. The country spends 40–50% of its total export income to import fuel, mainly crude oil and natural gas. The following energy and econometric data for the year 2009 will enable an assessment that pertains to the present study: energy consumption of 1370 kg of oil equivalent per capita annually (18,100 kWh/capita annum) and bank interest rates of 6.5%. Tables 1 and 2 provide data respectively on Turkey's external energy dependence and the per capita energy use [2]. Fig. 1 on the other hand presents the sectoral breakdown of final energy consumption of 71.857 (1000 toe) in Turkey as of 2008 [3].

Major price change in gas supply from Russia is now an inducement for investment in solar energy within Turkey with 45% of its electricity delivered by gas. Natural gas production in Europe is declining while demand will grow over the foreseeable future. The International Energy Agency (IEA) has determined that imports will thus grow from 35% of demand in 2009 to 65% of demand by 2030. Within the member states of EU-27 the expected growth in energy demand will reach over 80% by 2030 [4]. With gas being sourced predominantly from Russia with the latter providing 25% of OECD European consumption, countries such as Turkey would be well advised to switch to a more sustainable energy source such as solar PV.

Table 3 provides further information on energy and economy for Turkey and places it in contrast to the relevant data for the EU and the world [5]. Fig. 2 presents information on the fuel-mix for electricity generation. Of particular note is the heavy use of coal and imported gas.

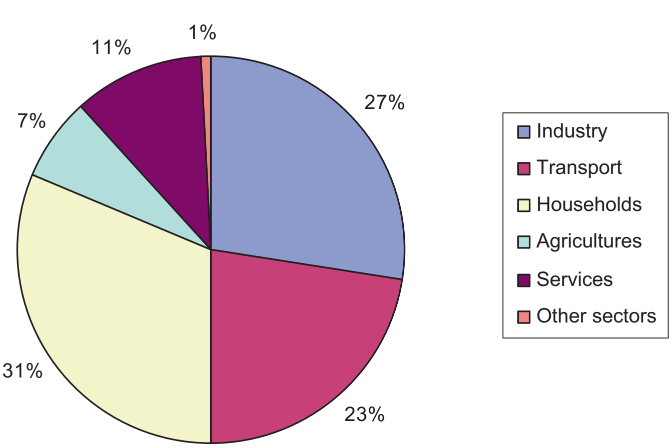

Fig. 1. Sectoral breakdown of final energy consumption in Turkey.

Table 3
Energy data for Turkey.

Turkish per capita energy consumption	15,933 kWh/annum
EU per capita energy consumption	47,440 kWh/annum
World per capita energy consumption	19,460 kWh/annum
Turkish annual increase of energy consumption	8%
Turkish per capita electricity consumption	2732 kWh/annum
EU per capita electricity consumption	5930 kWh/annum
World per capita electricity consumption	2625 kWh/annum
Turkish annual increase of electricity consumption	6%
Energy cost data for Turkey, domestic sector (June 2010 data)	
Petroleum	1.9 Euro/l
Diesel	1.5 Euro/l
Electricity	12.8 Euro cents/kWh

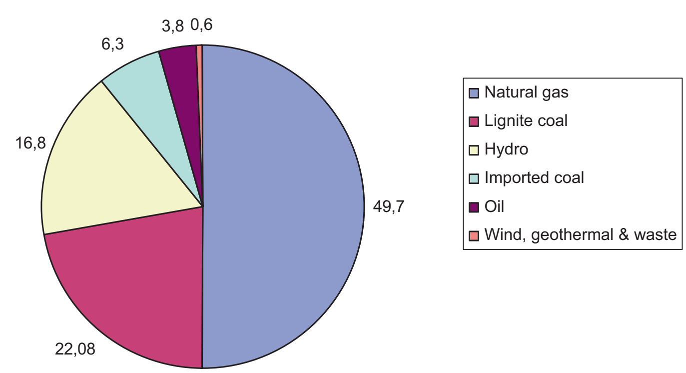

Fig. 2. Turkish electricity generation by fuel type.

2. Wind power and its environmental impact for Turkey

Turkey's income level is rapidly moving towards that of the rest of the OECD area. This catch-up process has been associated with a rapid growth of greenhouse gas (GHG) emissions. The Turkish government is now in the process of developing a strategy to reduce the growth of GHGs. This strategy will be elaborated in the context of Turkey's adhesion to the United Nations Framework Convention on Climate Change. Turkey passed the national legislation to ratify the convention in January 2004. Following adhesion, Turkey has the obligation to implement measures and polices to mitigate GHG emissions [6]. It is acknowledged that the potential of wind energy to curb global emissions is crucial for the long-term sustainability of the power sector [7]. Wind power is an environmentally clean, emission-free power generation technology. Like all renewable sources it is based on capturing the energy from natural forces and

has none of the polluting effects associated with 'conventional' fuels [8]. On the other hand, first and foremost, wind energy produces no carbon dioxide, which is the main greenhouse gas contributing to climate change during its operation, and minimal quantities during the manufacture of its equipment and construction of wind farms. By contrast, fossil fuels such as coal, gas and oil are major emitters of carbon dioxide [8–10]. As in the world, the power sector today accounts for a significant percentage of carbon dioxide emissions in Turkey. Therefore, a change of attitude in Turkey's energy policy to move towards renewable energy based power production is of great consequence.

3. Wind energy potential and utilization

Turkey has significant wind energy potential because of its geographical characteristics, such as its shoreline and mountain-valley structures [11]. The wind sources in Turkey are concentrated in the western and southern regions of Turkey. The sea fronts of the Agean, Marmara, Mediterranean, and Black Seas, and some places of the Southeast Anatolian belt have a high wind potential, with an average speed of 4.5–10 m/s [12]. Some of the studies put wind-energy potential in terms of the technical aspects in the region of 80 GW [13,14], while some others reported that Turkey's technical and economical wind energy potentials were 83 GW and 10 GW, respectively [15,16].

According to the wind atlas of Turkey prepared by the General Directorate of Electrical Power Resources of Turkey (EIE) using the data obtained from the Turkish State Meteorological Service (DMI) and neighbour countries, the economic potential is 10 GW and the technical potential is 88 GW [17]. Further research to determine the technical wind potential of Turkey carried out in 2006 by the EIE wind energy potential at 50 m above ground level in land regions was calculated as 131,756 MW, which is equivalent to a wind power density greater than 300 W/m^2 [18].

Since the first wind-based power plant started operation in the Izmir-Cesme-Germiyan region in 1998 with an installed capacity of 1.5 MW, the total installed capacity reached 333.35 MW as of 2008 [19] and 727.45 MW at the end of 2009 with a total of 28 operating wind power plants [16]. The installed capacities of the wind power plants vary from 0.85 to 90 MW [20]. With the rapid growth experienced, presently, wind power represents more than 1% of the total installed power capacity in Turkey. Energy investors have already applied for further 751 wind projects, which would bring the installed wind capacity to 78 MW [21], which is almost two times greater than Turkey's total installed capacity. Of these, 73% are for the Marmara and Agean regions, while those for Izmir and Çanakkale make up 15 and 12.5%, respectively, of all the applications.

4. Case study for Çanakkale region

As one of the locations with most wind potential, and having 10% of the installed wind capacity in Turkey, Çanakkale province has been chosen presently for the case study. Çanakkale is a province in Turkey, located in the northwestern part of the country. It takes its name from the city of Çanakkale. Çanakkale province has a European (Thrace) and an Asian (Anatolia) part. The European part is formed by the Gallipoli (Gelibolu) peninsula, while the Asian part is largely coterminous with the historic region of Troad in Anatolia. They are separated by the Dardanelles strait, connecting the Sea of Marmara and the Aegean Sea. Most of the land of the province is in the Marmara region while smaller part is in the Aegean region (see Fig. 3).

The current paper presents an investigation of the wind power potential of the city centre of Çanakkale (which will be referred to as Çanakkale hereafter) and Bozcaada, which is an island town of Çanakkale in the Aegean Sea, using hourly wind data measured by the DMI. The obtained wind characteristics were statistically analysed using the Weibull and Rayleigh distribution functions.

Fig. 3. Map of Çanakkale province.

4.1. Analysis of wind speed and direction

In the present study, hourly time-series wind data belonging to Çanakkale and Bozcaada has been analysed. The data was recorded from the year 2000 to 2005 at a height of 10 m.

Starting from the basics, the mean and its standard deviation can be calculated using the time-series wind speed data by,

$$v_m = \frac{1}{N}\left[\sum_{i=1}^{N} v_i\right] \tag{1}$$

$$\sigma = \left[\frac{1}{N-1}\sum_{i=1}^{N}(v_i - v_m)^2\right]^{1/2} \tag{2}$$

Alternatively, if the probability density function that represents the wind data is known, the mean wind speed can be determined from

$$v_m = \int_0^{\infty} v f(v)\, dv \tag{3}$$

The monthly mean wind speed values for the available time-series data at 10 m height are presented in Figs. 4 and 5 for Bozcaada and Çanakkale, respectively, for the years from 2000 to 2005. For the former location, the highest monthly mean wind speed of 9.59 m/s occurred in February in 2003. For the latter location, the highest monthly mean wind speed of 6.02 m/s occurred in February in 2005. For Bozcaada, the highest annual mean wind speed was 6.47 m/s in 2003 while it was 4.75 m/s for Çanakkale in 2004. From the available six years long of data, one year has been chosen for each location as the typical year and analysed, which are the calendar years of 2004 and 2001 for Bozcaada and Çanakkale, respectively.

The wind speed data in time-series format is usually arranged in the frequency distribution format since it is more convenient for a statistical analysis. The annual probability density and cumulative frequency distributions obtained from the time-series data are presented in Fig. 6 for the locations analysed. The probability distributions and the functions representing them mathematically are the main tools used in the wind energy-related literature. Their

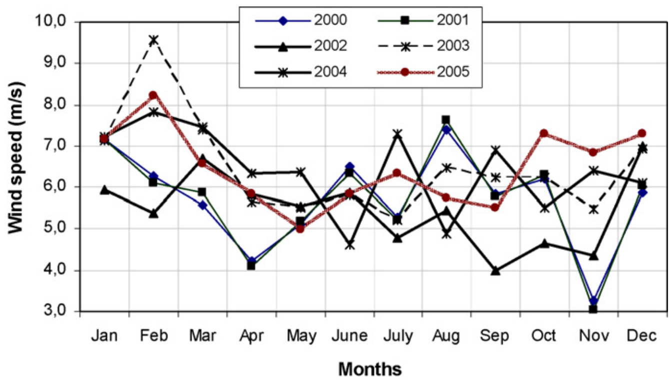

Fig. 4. Monthly mean wind speed values for Bozcaada for the years from 2000 to 2005.

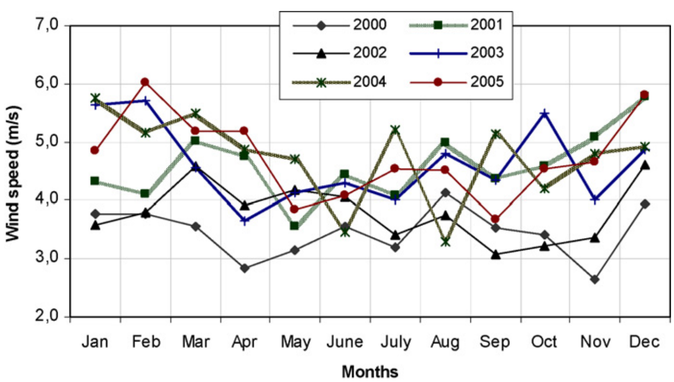

Fig. 5. Monthly mean wind speed values for Çanakkale for the years from 2000 to 2005.

use includes a wide range of applications, from analysing the wind speed data to the wind energy economics [22,23]. Two of the commonly used functions for fitting a measured wind speed probability distribution in a given location over a certain period of time are the Weibull and Rayleigh. The probability density function for the Weibull distribution is given by,

$$f_W(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right] \tag{4}$$

where c is the scale parameter and k is the shape parameter. The corresponding cumulative probability function of the Weibull distribution is,

$$F_W(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)\right]^k \tag{5}$$

Table 4
Weibull parameters of c and k for the chosen typical annual wind data for the locations under study.

	Bozcaada		Çanakkale	
	c	k	c	k
January	8.07	1.61	4.85	1.66

The Weibull parameters calculated analytically are presented in Table 4 for the two locations under investigation. There are several methods presented in the literature to identify the parameters of the Weibull function [24–26].

The Rayleigh model is a special and simplified case of the Weibull model. It is obtained when the shape factor k of the Weibull model is assumed to be equal to 2. The probability density and the cumulative distribution functions of the Rayleigh model are given by,

$$f_R(v) = \frac{\pi}{2}\frac{v}{v_m^2} \exp\left[-\left(\frac{\pi}{4}\right)\left(\frac{v}{v_m}\right)^2\right] \tag{6}$$

$$F_R(v) = 1 - \exp\left[-\left(\frac{\pi}{4}\right)\left(\frac{v}{v_m}\right)^2\right] \tag{7}$$

One of the most distinct advantages of the Rayleigh distribution is that the probability density and the cumulative distribution functions could be obtained from the mean value of the wind speed. The Rayleigh model has also widely been used to fit the measured probability density distribution and its validity was shown for various locations by the researchers [27–29].

The Weibull and Rayleigh distributions fitted to the time-series probability density distributions for Bozcaada and Çanakkale are seen in Figs. 7 and 8, respectively. It can be observed in Fig. 7 that the most frequent wind speed expected in the area under investigation is around 6 m/s, a value which corresponds to the peak of the probability density curve. This result agrees with that already obtained from the initial analysis of the mean wind speed. It is also clear in Fig. 7 that the chances of wind speed exceeding 20 m/s in this region were very limited. As expected from the lower mean wind speed value for Çanakkale, the most frequent wind speed expected is around 2 m/s for this location, a much smaller value than that for Bozcaada.

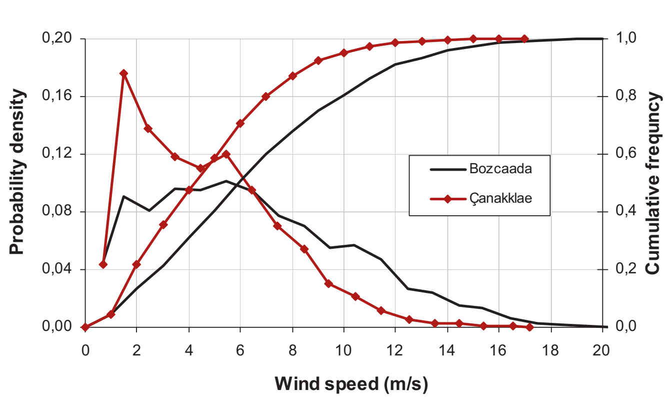

Fig. 6. Probability density and cumulative frequency distributions for the typical annual wind speeds for Bozcaada and Çanakkale.

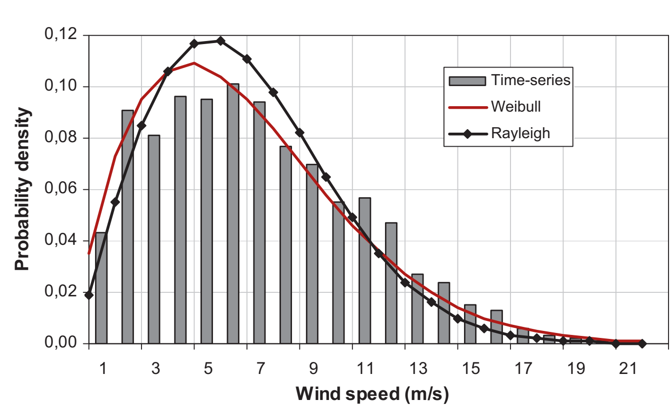

Fig. 7. Probability density distributions obtained from the measured and the Weibull and Rayleigh models for Bozcaada.

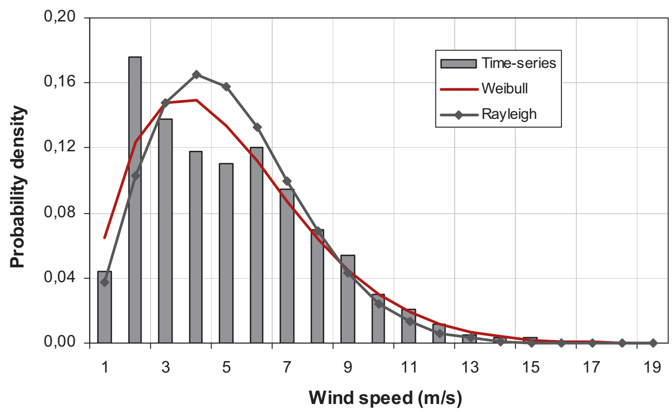

Fig. 8. Probability density distributions obtained from the measured and the Weibull and Rayleigh models for Çanakkale.

4.2. Analysis of wind power density

The power of the wind per unit area is given by

$$P = \frac{1}{2}\rho v^3 \tag{8}$$

Then, the mean wind power density P_m can be calculated from the measured probability density distribution using the following equation,

$$P_m = \sum_{j=1}^{n}\left[\frac{1}{2}\rho v_{m,j}^3 f(v_j)\right] \tag{9}$$

This parameter serves as the 'reference mean power density' and designated $P_{m,R}$. On the other hand, the most general equation to calculate the mean wind power density is,

$$P_m = \int_0^\infty P(v)f(v)\,dv \tag{10}$$

However, the mean wind power density can be calculated directly from the following equation if the mean value of v^3, which is $(v^3)_m$, is already known,

$$P_m = \frac{1}{2}\rho(v^3)_m \tag{11}$$

From Eq. (4), the mean value of v^3 can be determined as

$$(v^3)_m = \int_0^\infty v^3 f(v)\,dv \tag{12}$$

Integrating Eq. (12), the following is obtained for the Weibull function,

$$(v^3)_m = \frac{\Gamma(1+3/k)}{\Gamma^3(1+1/k)}(v_m)^3 \tag{13}$$

Note that the gamma function has the properties of $\Gamma(x) = \int_0^\infty \xi^{x-1}\exp(-\xi)\,d\xi$ and $\Gamma(1+x) = x\,\Gamma(x)$.

If Eq. (3) is solved together with Eq. (4) making the substitution of $\xi = (v/c)^k$ for v, the following is obtained for the mean wind speed,

$$v_m = c\,\Gamma\left(1+\frac{1}{k}\right) \tag{14}$$

Introducing Eqs. (13) and (14) into Eq. (11), the mean power density for the Weibull function would be,

$$P_W = \frac{1}{2}\rho c^3\,\Gamma\left[1+\frac{3}{k}\right] \tag{15}$$

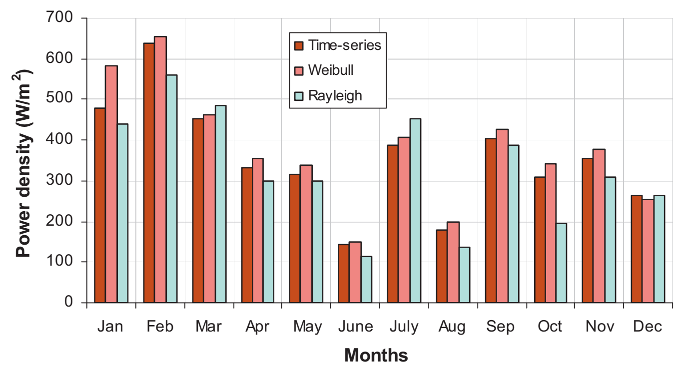

Fig. 9. Monthly mean power density values calculated from the measured probability density distributions and those obtained from the Weibull and Rayleigh models for Bozcaada.

For $k = 2$, the following is obtained from Eq. (14),

$$v_m = c\sqrt{\frac{\pi}{4}} \tag{16}$$

By extracting c from Eq. (16) and setting k equal to 2, the power density for the Rayleigh model is found to be,

$$P_R = \frac{3}{\pi}\rho v_m^3 \tag{17}$$

The monthly mean power density values calculated from the measured probability density distributions and those obtained from the Weibull and Rayleigh models are given in Figs. 9 and 10 for the typical years for Bozcaada and Çanakkale, respectively. The power density values show a large month-to-month variation for both locations. The minimum power densities occur in June 143.41 W/m^2 for Bozcaada and May as 63.63 W/m^2 for Çanakkale. The highest power density values are 638.46 W/m^2 in February for the former and 232.09 in December for the latter locations. The annual mean power densities are 354.75 W/m^2 for Bozcaada and 139.18 W/m^2 for Çanakkale.

The errors in calculating the mean power densities using the models in comparison to those using the measured probability density distributions can be calculated using the following formula,

$$\text{Error}\,(\%) = \frac{P_{W,R} - P_{m,R}}{P_{m,R}} \tag{18}$$

The Weibull model returns smaller error values in calculating the power density for Bozcaada when compared to the Rayleigh model. For this location, the highest error value occurs in January with 22.0% for the Weibull model. The power density is estimated by the Weibull model with a very small error value of 0.2% in March.

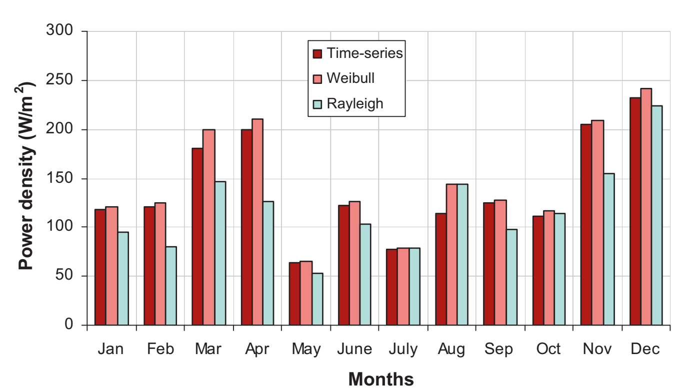

Fig. 10. Monthly mean power density values calculated from the measured probability density distributions and those obtained from the Weibull and Rayleigh models for Çanakkale.

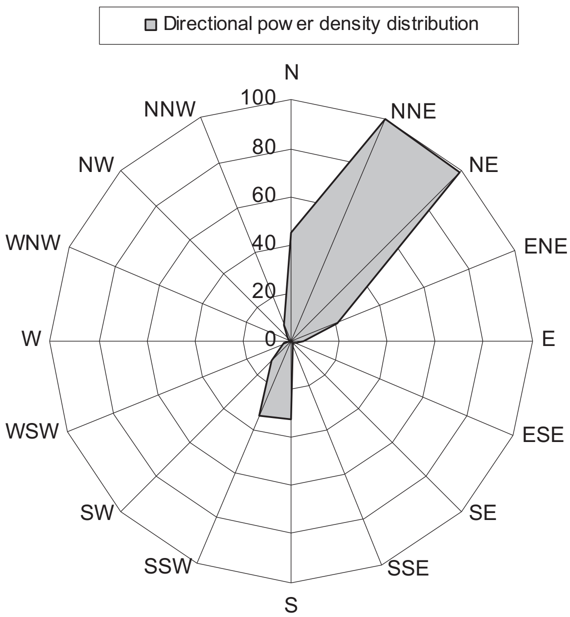

Fig. 11. Annual directional power density distribution for Bozcaada for the typical year.

The annual average error value in calculating the power density using the Weibull function is 7.3%, employing the following equation

$$\text{Error (\%)} = \frac{1}{12}\sum_{i=1}^{12}\left|\frac{P_{W,R} - P_{m,R}}{P_{m,R}}\right| \tag{19}$$

The monthly analysis shows that the error values in calculating the power density using the Rayleigh model is relatively higher for Çanakkale, over 35% in some months such as October. The annual average error value in estimating the power density using the Rayleigh model is 13.0%.

4.3. Directional analysis of wind potential

For wind energy investigations the study and prediction of the wind direction and directional power density distribution is highly important. It is acknowledged that the best wind sector based on time (directional wind speed) does not necessarily coincide with the best sector based on the available wind power (directional power density) [30]. Therefore, combination of the two different directional parameters into one as directional power density distribution is considered presently for the directional analysis undertaken. Annual directional power density distribution for Bozcaada for the typical year is given in Fig. 11. Most of the times the prevailing wind power in Bozcaada are in the north–northeastern, the northeastern, and in the south–southwestern and southern directions. This is indeed what is most expected because Bozcaada is an island in the Aegean Sea located very near to the exit of the Dardanelles, thus at the receiving end of the northern winds blowing from the Sea of Marmara. Note that over 60% of wind energy comes from the band between northern and northeastern directions. This is favourable as it means a significant stability for the directional power density distribution in Bozcaada.

Separate analysis of directional probability and power densities for the case of Bozcaada shows that the mean power density value in the northeastern direction is highest for the typical year with a value of 901.6 W/m^2, while the directional probability density value for the same sector is 11%. However, the mean power density is 493.2 W/m^2 in the north–northeastern direction but with a directional probability density value of 20%. Thus the power density is highest in the north–northeastern direction with 99.9 W/m^2, while it is 98.8 W/m^2 in the northeastern direction.

5. Conclusions

In the present study, hourly time-series wind speed data of Çanakkale and Bozcaada have been statistically analysed. The wind energy potential of the locations has been studied based on the Weibull and the Rayleigh models at a height of 10 m. The results from this investigation showed that the former location, with a mean wind speed of 4.6 m/s for the typical meteorological year, falls under class 2 of the international system of wind classification and the corresponding annual mean power density was estimated to be 140 W/m^2, which is generally sufficient only for small, household scale applications. However, with favourable characteristics the latter location offers a high wind potential.

The conclusions reached are summarised next:

- Çanakkale province is one of the two regions with the most wind potential in Turkey. Having an annual mean wind speed over 7 m/s (at 50 m height), most of the region offers excellent conditions for large scale wind energy applications.
- At 50 m height, over 70% of the land in Çanakkale province has the potential for a capacity factor of 35% or over and at least 25% of the land is ideal for large scale wind energy applications, offering a total installable power capacity of about 13,000 MW.
- Bozcaada is one of the most suitable locations in Çanakkale province, having already a wind farm installed with a capacity of 10.2 MW. Most of its land is suitable for wind energy applications with a capacity factor of 40% or over. The conclusions drawn from the investigation into the wind data for the typical meteorological year for Bozcaada island are:
- The windiest month is February with the mean wind speed reaching 7.8 m/s, while the calmest month is June having the mean wind speed value under 5 m/s. The annual mean wind speed is approximately 6.4 m/s.
- The monthly mean wind density values are high enough to be classified as class 6 in four months, January, February, March and September, having the density values higher than 400 W/m^2, while they fall under either class 2 or 4 in June, August and December. In the remaining months the mean power densities fell onto the wind power class of 5. Overall, this particular site falls under class 5 with the mean density value higher than 350 W/m^2, indicating sufficient wind potential for large scale electricity generation.
- The mean power density value in the northeastern direction is highest for he typical year in Bozcaada with a value of 901.6 W/m^2, while the directional power density distribution shows that over 60% of wind energy comes from the band between northern and northeastern directions.
- For the typical year under investigation, the Weibull parameters c and k were found to be 7.2 m/s and 1.8, respectively.
- As indicated both from the probability density distribution and the mean power density analysis, the Weibull model was found to be better in representing the measured data.

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